JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 4, July–August 2002

Space Systems Flexibility Provided by On-Orbit Servicing: Part 2

Elisabeth Lamassoure,* Joseph H. Saleh,† and Daniel E. Hastings‡
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Spacecraft are still the only complex engineering systems without routine maintenance infrastructure. Whereas the technologies for autonomous on-orbit servicing of satellites are emerging, no general conclusions have yet been drawn regarding the cost effectiveness of on-orbit servicing. In a companion paper (Saleh, J. H., Lamassoure, E., and Hastings, D. E., "Space Systems Flexibility Provided by On-Orbit Servicing: Part 1," *Journal of Spacecraft and Rockets*, Vol. 39, No. 4, 2002, pp. 551–560), a new perspective on the problem was proposed, in which the value of servicing is studied independently from its cost. A framework to account for the value of the flexibility provided by on-orbit servicing to space systems was developed. Here, the usefulness of this framework is demonstrated by studying the value of servicing for two types of space missions. First commercial missions with uncertain revenues are considered. It is shown that traditional valuation has been underestimating mission value by not taking into account the option to abandon. Then servicing is considered as an option on life extension, showing how the optimal design life decreases with increasing uncertainty. A map of the maximum servicing price in a market level/market volatility space is proposed as a new tool for decision making. Then military missions faced with uncertainty in the location of contingencies are considered. The value of refueling for making spacecraft maneuverable is studied for two cases. For a radar constellation in low Earth orbit, servicing is shown to have little value due to a conflict between propulsion mass and maneuver time. For a geostationary fleet of communication satellites, servicing is shown to have value based on the potential improvements in capacity usage.

Nomenclature

B	=	learning curve factor, %
C_D	=	development costs, $
C_{IOC}	=	cost to initial operating capability, $
$C_k^{(n\to m)}$	=	cost at T_k to switch from mode n to mode m, $
C_L	=	launch cost per unit mass, $/kg
C_S/C_{Sm}	=	servicing price per operation/per unit mass, $
cd	=	cumulative discount function, $cd(\tau, r)$ is equal to $(1-e^{-r\tau})/r$, year
$EV_{\geq k}^{(m)}(x)$	=	mission value incurred after T_k in mode m if $X^{(m)}(T_k)=x$
f_p	=	propulsion dry mass factor
f_{st}	=	structures mass factor
g	=	gravitational acceleration at Earth's surface, m/s^2
I	=	integer part function where $I(x)$ is integer and $I(x)\leq x<I(x)+1$
I_{sp}	=	specific impulse, s
$M_{\mathrm{dry}}^{\mathrm{base}}$	=	satellite dry mass without propulsion system, kg
$\mathcal{M}_{th}(t)$, $\mathcal{M}(t)$	=	forecast/actual revenues rate at t in mode m, $/year
$o_p^{(m)}$	=	operations cost per unit time for a mission in mode m, $/year
P_C	=	probability of a catastrophic event during servicing
P_{input}	=	total available spacecraft input power, W
$P_k(t)$	=	probability to be in state k at t
r	=	risk-free interest rate, %/year
T_D	=	spacecraft design lifetime, year
T_H	=	time horizon over which missions are evaluated, year
T_k	=	kth decision point, year
T_0	=	orbital period at the altitude a_0, s
$u^{(m)}(t)$	=	utility rate at t for a mission in mode m
V_0	=	orbital velocity at the altitude a_0, m/s
$X^{(m)}(t)$	=	uncertain parameter at t for a mission in mode m
α	=	effective rate-of-return of a commercial project, %/year
$\Delta T_{\max}$	=	maximum time allowed for a maneuver, s
ΔV_{inc}	=	incremental velocity required for orbit insertion, m/s
$\Delta V_{\max}$	=	maximum velocity increment before needed refueling, m/s
$\Delta\Phi$	=	baseline phase between two coplanar satellites, deg
ϵ	=	fuel fraction carried on spacecraft during launch
μ_M	=	maneuver rate, year^{-1}
μ_S	=	servicing rate, year^{-1}
ν	=	theater frequency, year^{-1}
ν_c	=	contingency frequency, year^{-1}
σ	=	volatility of a commercial project, %/year$^{1/2}$
τ_k	=	kth period, $T_{k+1}-T_k$, year

Received 18 June 2001; revision received 1 February 2002; accepted for publication 11 February 2002.

*Research Assistant, Department of Aeronautics and Astronautics; currently Engineer, Advanced Space Concepts, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125; elisabeth.lamassoure@alum.mit.edu. Member AIAA.

†Research Assistant, Department of Aeronautics and Astronautics; currently Associate, McKinsey and Co., Washington, DC 20005.

‡Professor, Aeronautics and Astronautics and Engineering Systems, 33-413, 77 Massachusetts Avenue; hastings@mit.edu. Fellow AIAA.

Introduction

SPACECRAFT are still the only complex engineering systems without any maintenance, repair, and upgrade infrastructure. One-of-a-kind, reliable, and expensive spacecraft, designed for the longest possible lifetime, have been the result of this lack of space logistics. On-orbit servicing has long been recognized as having the potential to change the way business is carried out in space. However, its implementation requires a whole new way of designing and managing space systems. In addition, decision makers perceive it as a significant source of mission risk. For the move to on-orbit servicing to be actually deemed worthwhile, considerable advantages in terms of cost effectiveness must be proven.

Several studies proposed architectures for autonomous on-orbit servicing of specific space missions and demonstrated potential improvements in terms of cost or cost effectiveness.[1–5] However, no advantages have been proven to date that outweigh the perceived risk and cost uncertainty.

With the need to study the full value of servicing independent from its cost recognized, the companion paper[6] proposed a new approach to on-orbit servicing. When decision tree analysis and real options theory were built and expanded, Saleh et al.[6] defined a framework to embed the value of flexibility into the valuation of space missions faced with external sources of uncertainty after they have become operational. The framework relies on the definition of a few building blocks, the most important being a model of the uncertainty, a set of reachable operational modes, a sequence of decision points, and a definition of mission value. The cornerstone of the framework is to consider that at each future decision point, the mode of operation that maximizes future value will be chosen on the basis on the latest available information on the uncertain parameter. Mission value can then be estimated through a backward iterative process very similar to a decision tree with infinite number of branches.

To be fully validated, this model should be applied to different types of space missions that have different value metrics and different sources of uncertainty. In this paper, we consider two cases, chosen because they are very different from each other but both very typical of situations of high uncertainty encountered by the space industry: commercial missions with uncertain market demand and military missions with dynamic contingency locations.

The linearity of mission value makes commercial missions with uncertain revenues a particularly simple case, very close to real options valuation. Saleh et al.[7] identified the gap between the long design lifetime of space systems and the often shorter timescales of market dynamics and suggested a trade between design lifetime requirement and flexibility. We will see how this trade can be explored and quantified by considering on-orbit servicing as an option on life extension.

The case of military missions with dynamic theater location is more complex. First, contingencies can move at any time, requiring on-demand maneuvering and making the decision points continuous. Furthermore, value takes the form of a utility per cost and is, thus, not linear. For these reasons, both real options theory and decision tree analysis are impractical. The last part of this paper explores the extension of the framework for such missions. It studies the value of refueling to make a constellation of satellites maneuverable for two cases: a low-Earth-orbit (LEO) radar constellation using the example of the Discoverer-II project and a geostationary fleet of communication satellites using the example of the Defense Satellite Communications System (DSCS).

Commercial Missions with Uncertain Revenues

One of the most typical situations in which a significant source of uncertainty affects a space system is the case of a commercial mission with uncertain revenues. This section proposes to investigate two complementary ways to mitigate the risk associated with this uncertainty. It first considers an option that is available to all space missions: the option to abandon the mission if the operational costs exceed the revenues. It then addresses the possibility to design spacecraft for a shorter lifetime with the option to service for life extension if the market booms. This option represents a source of flexibility that would be available only to serviceable space missions. Traditional valuation, which is based on net present value (NPV) calculations, would underestimate the value of these missions by not accounting for the flexibility of decision makers to shut down or extend the missions as events unfold. We will see how the new valuation framework overcomes this shortcoming of the traditional approach.

Baseline Assumption

Before proceeding with the valuation of options, assumptions on the form of the uncertain parameter must be made. Most commercial missions start off with a forecast $\mathcal{M}_{th}(t)$ for their future revenues per unit time. The uncertain parameter can be defined as the ratio of the actual potential revenues over their forecast:

$$X = \mathcal{M}(t)/\mathcal{M}_{th}(t) \tag{1}$$

The goal of this study being to capture the value of the option to abandon or service, which does not directly affect these potential revenues, it is fair to assume that this source of uncertainty is external to the system. As is often the case in real options theory,[8] we will further assume that the uncertain parameter is a geometric random walk process with drift α and volatility σ. Then if $X(t)$ is known, $X(t+\tau)/X(t)$ has the probability density function

$$p_\tau(x) = \frac{1}{\sqrt{2\pi}}\frac{1}{\sigma\sqrt{\tau}}\frac{1}{x}\exp\left\{-\frac{[\ln(x)-(\alpha-\sigma^2/2)\tau]^2}{2\sigma^2\tau}\right\} \tag{2}$$

This assumption simplifies calculations while capturing two relevant features. First, the Gaussian distribution that results is a valid approximation when the observed uncertainty is the sum of many independent uncertain parameters, which is often the case for the market dynamics that make revenues vary. In addition, the standard deviation varies as $\sqrt{\tau}$, which is a good description of the increase in uncertainty as one makes predictions further away in time.

General Backward Iterative Process

Given this assumption on the uncertain revenues, the following valuation process can be used for all commercial cases. The decision makers at $t = 0$ anticipate their future flexibility: At each decision point T_k, a mode of operation will be chosen on the basis of the previous mode of operation l and the observed value of the uncertain parameter $x = X(T_k)$. The new optimal mode n will be obtained by maximizing the future value

$$EV_{\geq k}^{(l\to n)}(x) = x^{(n)}\int_0^{\tau_k}\mathcal{M}_{th}^{(n)}(T_k+t)e^{(\alpha_n-r)t}\,\mathrm{d}t - C_k^{(l\to n)} + \cdots + e^{-r\tau_k}\sum_{m=1}^{N_M}\int_{I_{k+1}^{(n\to m)}} EV_{\geq k+1}^{(n\to m)}(y)\,p_{\tau_k}(y|x)\,\mathrm{d}y \tag{3}$$

This process gives the sets $I_k^{(l\to n)}$ of values of the uncertain parameter x for which a switch to mode n will be optimal at T_k. Thus, with knowledge of the functions $EV_{\geq k+1}(x)$, Eq. (3) gives the functions $EV_{\geq k}(x)$. Iterating from the last decision point back to $T_0 = 0$, this process gives the expected mission value $V = EV_{\geq 0}^{(0)}(1)$. This expanded NPV takes into account the future capacity to make optimal decisions.

Compound Option to Abandon

The option most immediately available to space systems is the option to abandon the mission if the operational costs are considered too high. The value of this option has never been taken into account in the literature. Its simplicity makes it a good candidate for a first application of the model.

Model

The decision points for the periodic option to abandon with period τ_a are $T_k = k\tau_a$. At these times the mission can choose between two modes of operation: not operational mode 0 and operational mode 1. The revenues rate in mode 0 is $u^{(0)} = 0$ and in mode 1 is $u^{(1)}(t) = X\mathcal{M}_{th}(t)$. To model the effect of the abandoning option alone, we will here assume a constant market forecast $\mathcal{M}_{th}(t) = \mathcal{M}_0$. When it is assumed that it costs nothing to abandon the mission, that is, the costs to deorbit are included in the form of additional propellant in the initial design, but the operational cost to deorbit is assumed to be small, the costs to switch between the two modes of operation can be represented at each decision point by the matrix of switching costs:

$$(C_k) = \begin{pmatrix} 0 & o_p\cdot cd(\tau_a,r)+C_{\text{reinit}} \\ 0 & o_p\cdot cd(\tau_a,r)\end{pmatrix} \tag{4}$$

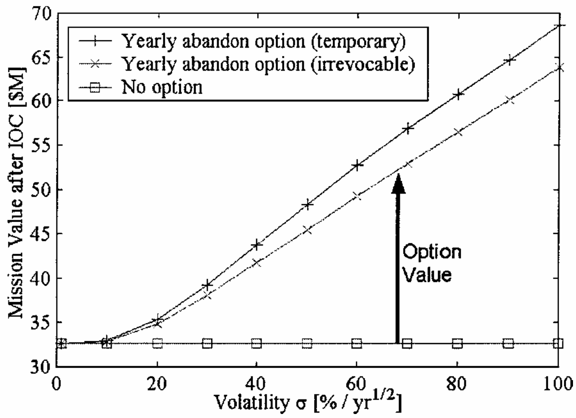

Fig. 1 Value of the compound abandon option.

Results

The results depend on costs in a relative manner only. For example, if O_p are the total operations costs over the mission in the absence of an abandonment option, $O_p = o_p \cdot cd(T_H, r)$, no generality is lost by expressing $\mathcal{M}_0$ and V as percentages of O_p. Similarly, the results depend on time only through the products σt, αt, and rt, so that the option value V is actually a function of only five variables:

$$V/O_p = f^n\left(\mathcal{M}_0/O_p, T_H/\tau_a, \sigma\sqrt{T_H}, r\,T_H, \alpha T_H\right) \quad (5)$$

As expected, the value of the compound option to abandon increases with the number of options over the lifetime; however, it quickly reaches an upper bound at around six options. Figure 1 shows this upper bound as a function of uncertainty for a mission horizon of $T_H = 15$ year, a risk-free interest rate (discount rate) of $r = \alpha = 5\%$/year, a market forecast $\mathcal{M}_0 = \$8$ million/year, and an operations cost $o_p = \$5$ million/year. The value of the irrevocable abandon option, for which $C_{\text{reinit}} = \infty$, and the value of the temporary abandon option, for which $C_{\text{reinit}} = 0$, are a lower and upper bound on the value of a realistic option. Figure 1 shows that these bounds are close enough to make any detailed modeling of the reinitiation cost unnecessary. It also shows how the value of the abandon option increases linearly with uncertainty. For $\sigma = 100\%/\text{year}^{1/2}$, traditional valuation would have underestimated the net mission benefits after initial operating capability (IOC) by a factor of 2.

Conclusion

These results show that traditional valuation methods have been significantly underestimating the value of all missions with uncertain revenues, creating a bias in favor of conservative projects. When the flexibility of decision makers to shut off an unsuccessful mission is recognized, the proposed valuation framework shows that some projects that would be deemed uninteresting by traditional valuation can actually have significant value.

Thus, the application of the proposed framework proves useful even in the simple case of the option to abandon a space mission, which is a limited form of flexibility. It should prove even more interesting in studying the value of on-orbit servicing for space missions, which is the focus of the next section.

Optimal Design Life Under Market Uncertainty

The simplest option that servicing can give to space missions is the option on life extension. Figure 2 shows illustrates the traditional decision making process regarding the spacecraft lifetime requirement: As soon as the net present value of the mission is positive, satellites are launched with the longest possible lifetime. If a long lifetime only leads to high mass and cost due to the use of large design margins, it would be the optimal choice from a cost-per-operational day perspective.[7] However, as also noted in Ref. 7, this overlooks the presence of uncertainty. Traditional design lifetimes are often longer than the characteristic market life cycles, so that there is a fair risk that satellites will not respond to any actual market before their end of life. If on-orbit servicing were available, satellites could be designed for a period of time closer to the market

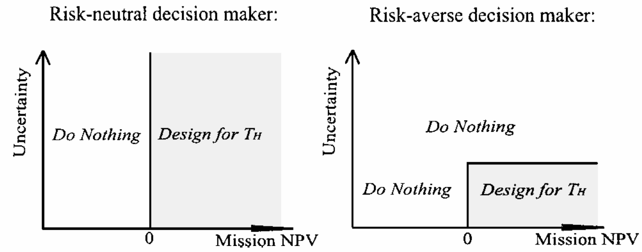

Fig. 2 Traditional decision making.

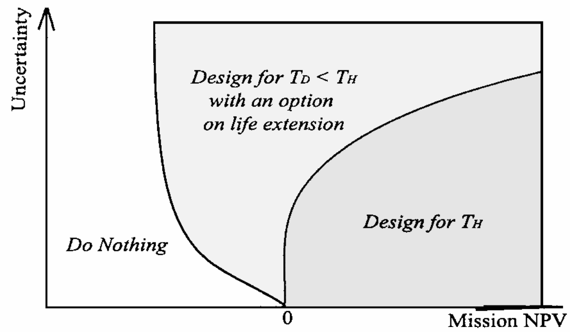

Fig. 3 Decision making with option on life extension.

dynamics, with the option to extend their life or abandon the mission according to the market conditions at a later time. The higher the uncertainty in the market, the more interesting this option is likely to be. Thus, taking uncertainty into account would lead to a new decision process as shown in Fig. 3. This section will show how the proposed valuation framework can quantify the boundaries in this decision diagram, identifying a minimum uncertainty level over which servicing is interesting. This minimum uncertainty will depend on the price of servicing. Thus, for a given level of uncertainty, there will be a maximum servicing price that makes the option on life extension interesting. This maximum price is an indication that if servicing is too expensive then designing for the longest possible lifetime is optimal. This consideration is independent of the choice of a servicing infrastructure: Therefore, it can be defined as the intrinsic value of servicing for the space mission.

Servicing and Optimal Design Life

Irrevocable Service or Abandon Option

Consider a space system designed for a time T_D with the option to be serviced in increments of the service interval τ up to the mission horizon T_H: The decision points are the service points $T_k = T_D + (k-1)\tau$ plus the yearly abandon option points $T_j = j\tau_a$. At each decision point, the system must choose between two modes of operations: mode 0 abandoned and mode 1 operational in its initial design.

The cost to IOC C_{IOC} is a function of the design life T_D; this function is studied in Ref. 7. For the purpose of this study, it is sufficient to use the following linear fit:

$$\frac{C_{\text{IOC}}(T_D)}{C_{\text{IOC}}(3\,\text{year})} = \frac{C_{\text{IOC}}}{C_3} = 1 + \kappa(T_D - 3\,\text{year}) \quad (6)$$

At $T_0 = 0$, the choice is between doing nothing and launching the space system for a cost $C_{\text{IOC}}(T_D) + o_p cd(T_D, r)$. At each servicing decision point, the choice is between abandoning the mission irrevocably for a negligible cost or deciding to service it and continue operations for the cost $C_S + o_p \cdot cd(\tau, r)$.

It is convenient here to define all monetary amounts as percentages of the cost to design for the arbitrary reference time of three years, $C_{\text{IOC}}(3\,\text{year}) = C_3$. The present value of the mission at time $T_0 = 0$ is finally a function of 10 parameters:

$$V/C_3 = f^n(T_D, C_S/C_3, \tau; \sigma, \mathcal{M}_{th}/C_3; o_p/C_3, \kappa, T_H, r, \alpha) \quad (7)$$

For the purpose of this analysis, the cost to make the satellites serviceable will be neglected for three reasons. First, whenever studied, this cost has been shown to be reasonably low.[9] Second, this work considered changing an existing design. If servicing is taken into account early in the design process, its impact can be expected to be even lower. Third, we are interested in determining an upper bound on the servicing price.

Optimal Design Life and Maximum Servicing Price

For a given servicing price and service interval, the optimal design life $\widehat{T_D}$ is the design life that gives the maximum expected mission value $\widehat{V_S}$. The maximum servicing price Υ is defined as the price under which this optimal design life is shorter than the mission horizon:

$$\widehat{T_D}(C_S/C_3, \tau, \ldots) < T_H \iff C_S/C_3 < \Upsilon$$

$$\Upsilon = f^n(\tau; \sigma, \mathcal{M}_{th}/C_3; o_p/C_3, \kappa, T_H, r, \alpha)$$

Lower Bound on Servicing Price

Whatever the choice of servicing infrastructure, it will be necessary to produce and launch the mass that has to be delivered to the serviceable spacecraft. Therefore, the cost to produce and launch this mass can be considered as a lower bound on the marginal cost of servicing and, hence, a lower bound on the servicing price. The cost relationship given by Eq. (6) suggests that this lower bound be approximated by

$$C_S/C_3 \geq \kappa\tau = \Upsilon_{\min} \tag{8}$$

Threshold Servicing Price in the General Case

Three of the eight parameters that set the value of the maximum servicing price are particularly interesting to study: the service interval τ, which is a free variable, and the market forecast $\mathcal{M}_{th}/C_3$ and the market volatility σ, which are the two parameters that can vary widely among space missions. The five remaining parameters will be held constant as indicated in Table 1. The value for the discount rates r and α in Table 1 were obtained by considering current aerospace industry data[10] and fitting the aerospace rate of return with the capital asset pricing model (CAPM).[11] The CAPM quantifies the link between risk level and required risk premiums.

Map of Threshold Servicing Price

Expressing the maximum servicing price Υ in units of its lower bound, $\Upsilon_{\min}$, makes the results almost independent of the servicing interval τ because of the linearity of the relationship between design lifetime and cost to initial operating capability [Eq. (6)]. Figure 4 maps the resulting maximum servicing price Υ in a market level/market volatility space. In a world of certainty ($\sigma = 0$), satellites should be designed for the longest possible lifetime as soon as the market is such as to produce a positive net present value. As uncertainty increases, the probability that the market will turn out higher than expected increases, increasing the value of any mission with an abandon option; this makes the threshold market decrease, as shown by the shape of the left boundary. However, an increasing uncertainty also increases the probability that the market shrinks significantly below expectations, making shorter design lifetimes more interesting. There appears a threshold uncertainty level over which a serviceable design is optimal; this level depends on the servicing price, as indicated by the labels on the design for servicing/design for horizon boundary curves.

The map of Fig. 4 accomplishes the goal of the section: It quantifies the boundaries on the decision making diagram envisioned in Fig. 3. These boundaries show that as soon as there is significant uncertainty about a market forecast, the price ΥC_3 that a commercial space mission should be willing to pay for servicing is an order

Table 1 Irrevocable service-or-abandon option: constant assumptions

Parameter	Notation	Baseline value	Source
Mission horizon	T_H	15 yr	Typical GEO
Risk-free interest rate	r	7.9%/yr	Adapted from Ref. 16
Rate of return	α	4.2%/yr	Adapted from Ref. 16
Penalty rate	κ	2.75%/yr	Adapted from Ref. 7
Operations costs per year	o_p	5% of C_3/yr	Typical[14]

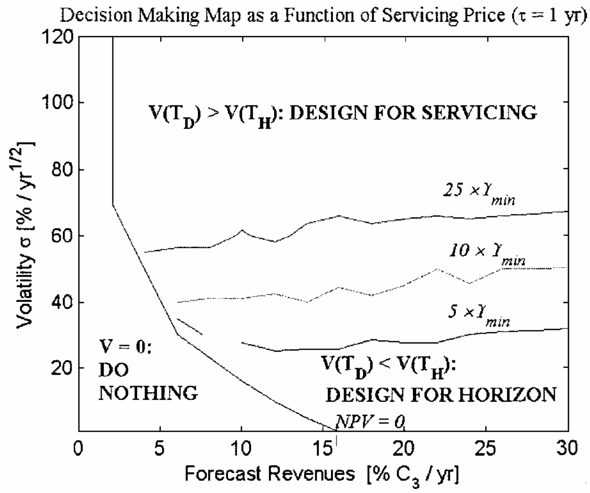

Fig. 4 Map of threshold servicing price for the option on life extension.

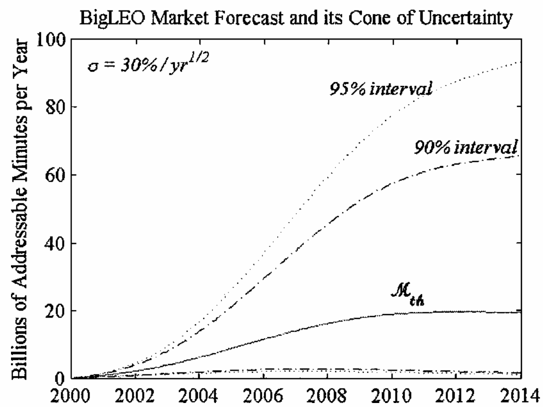

Fig. 5 LEO Communications market forecast (adapted from Ref. 12).

of magnitude higher than the estimated lower bound $\Upsilon_{\min} C_3$ on the marginal cost of servicing. Thus, Fig. 4 not only proves that on-orbit servicing can have significant value for commercial missions, it also shows that this conclusion can be reached only by accounting for the value of flexibility in the presence of uncertainty, which demonstrates the usefulness of the proposed framework.

In Fig. 4, the broad area labeled design for servicing corresponds to any design life shorter than the mission horizon. How does the optimal design life actually behave as uncertainty increases? Let us further explore this question by considering a realistic numerical example.

Application to Two LEO Communication Missions

Iridium and Globalstar

Iridium and Globalstar were two of the big LEO constellations of satellites conceived in the early 1990s to address the great potential market of mobile telephony. By the time the systems were launched, the market they had been expecting had shrunk significantly due to the advent and rapid evolution of cellular phones. The great uncertainty in their market make these two constellations perfect case studies for the valuation model.

The expected market for these missions as forecast in 1997 can be expressed in terms of number of billable minutes per year for various assumptions of market penetration.[12] This market is reproduced in Fig. 5, where a cone of uncertainty corresponding to $\sigma = 30\%$ year$^{-1/2}$ is represented for reference. The average price per minute was around \$3/min for Iridium and \$1/min for Globalstar. Combining these numbers with a typical market penetration of 10% gives the market forecast in terms of revenues, $\mathcal{M}_{th}(t)$.

Volatility

A major practical difficulty with any option valuation is the estimation of the volatility of the market. Although a market forecast is a necessary part of a business plan, the uncertainty in the forecast is by

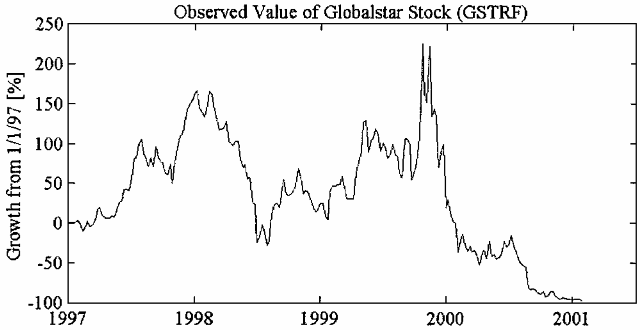

Fig. 6 Time variation of the Globalstar stock (GSTRF) (source http://finance.yahoo.com/).

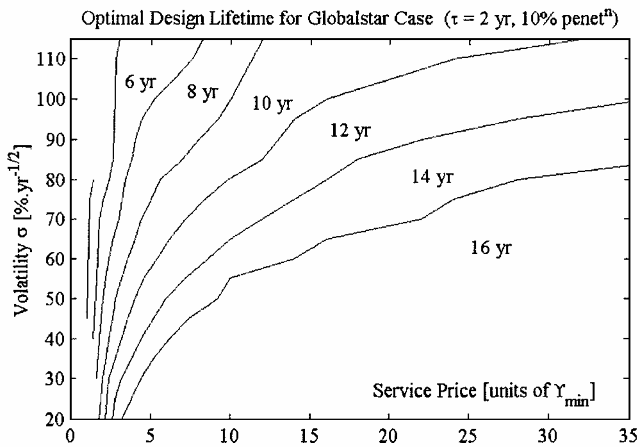

Fig. 7 Optimal design lifetime as a function of servicing price: Globalstar example.

definition unknown. In this case, however, an a posteriori volatility estimate is made possible by analyzing stock values such as plotted in Fig. 6. Figure 6 shows that the volatility of the Globalstar stock (GSTRF) has not been constant: Whereas $\sigma = 30\% \cdot \text{year}^{-1/2}$ could have been estimated at the start of the mission, a more realistic value given recent history would be $\sigma = 90\% \cdot \text{year}^{-1/2}$.

Results

The subsequent results correspond to making the following assumptions for Iridium and Globalstar, respectively: a cost to IOC of \$3 and \$2 billion, a required design lifetime of 5 and 7.5 years, and an operations cost of \$245 and \$125 million/quarter.

Figure 7 maps the regions of different optimal design lifetime for the parameters of the Globalstar case, in a service price/market volatility space. The map corresponding to the Iridium case is found to be very similar. As expected, the optimal design lifetime decreases with decreasing servicing price and increasing uncertainty. If servicing is very cheap (below two times the lower bound), then short design lifetimes make sense whatever the uncertainty. However, as the servicing price becomes significant, uncertainty becomes the main driver for the optimal design lifetime. In this case, an accurate estimation of the market uncertainty would be required to make the right decision. For example, the Globalstar volatility as estimated at the start of the mission would recommend the longest possible lifetime (here 16 years, barring any technological limit). However, the actual stock volatility as observed after five years corresponds to a shorter design lifetime with the option to service (here 6–12 years, depending on the servicing price).

Conclusion

These results validate the new approach of looking for an optimal design life, and show that on-orbit servicing can have significant value for commercial space missions with highly uncertain revenues. However, they also show that the practical application of the framework is not trivial; whereas it would provide decision makers with more information, it would also require more preliminary research than a simple net present value calculation.

Noncommercial Situations: Military Missions Case

The decision process for a military mission differs greatly from what happens in the commercial world. First, mission value is not a measure of revenues minus cost, but takes the form of a complex utility function divided by cost. Furthermore, there exists two decision processes. When designing a space mission during a peaceful time, the optimal design is the one the maximizes utility per cost under some constraints. However, when making a decision about an operational space mission involved in military contingencies, the cost factor becomes much less critical than the performance, and the alternative that maximizes utility is generally chosen.

This section proposes a way to adapt the framework developed in the companion paper to the special case of military missions faced with uncertainty in the location of contingencies over the world. The value of refueling as a way to make satellites maneuverable will be explored in two cases: a reduction in the number of satellites in a LEO radar constellation, and an improvement in capacity for a geostationary-Earth-orbit (GEO) fleet of communication satellites.

Thinned Radar Constellation

Space-based radar requirements are usually focused around a few critical theaters, whose location is expected to change several times over a mission lifetime. Therefore, space-based radar missions need to be designed with the flexibility to adapt to any possible theater location. Traditionally, this flexibility is build up in the system by designing the constellation for global coverage over the range of possible theater latitudes. This was, for example, the case for the Discoverer II project.[§] This constellation would consists of 24 low-cost satellites at 770-km altitude to meet a commander's requirement for an imaging operation within 15 min after receiving tasking (reaction time), 90% of the time, averaged over the inhabited latitudes. The project was deemed too expensive and was canceled.

The existence of a refueling capability in space could offer an cheaper alternative to global coverage for flexibility to theater location. A constellation designed for coverage over one location could maneuver to optimize its orbital characteristics for any new theater. Because it would require fewer satellites, such a system could be cheaper. This section proposes to evaluate the maximum servicing price that could make such a thinned constellation interesting.

Mission Value

A thinned constellation corresponds to a trade between the number of satellites and their maneuverability. For the trade to remain unbiased, satellite altitude and payload design will be held constant. Under these conditions, the design is driven by the requirement for a maximum availability at a minimum reaction time: $\mathcal{R}_b = (Av, Rxn) = (90\%, 15\,\text{min})$. Mission value will be the ratio of utility per cost, where utility is the total time in view of the instantaneous theater of interest.

Number of Satellites Versus Maneuverability

A good metric for maneuverability is the maximum incremental velocity that a satellite is designed to perform before it needs to be refueled. To gain some insight about maneuverability while keeping the study simple, let us further limit ourselves to Walker delta patterns[13] with a constant number of satellites $\mathcal{T}$ placed into a constant number of planes $\mathcal{P}$. An orbital configuration $\mathcal{C}$ is then defined by two numbers, namely, its inclination and its Walker phase number, $\mathcal{C} = (i, \mathcal{F})$. The incremental velocity required for a phase change being negligible compared to an inclination change, maneuverability can simply be expressed in terms of a maximum inclination change before running out of fuel, $\Delta i_{\max}$.

The more satellites that are available, the greater is the range of orbital inclinations and phase numbers that can meet the mission requirements over a given theater location. Therefore, increasing the number of satellites decreases their required inclination change capability. This trade can be quantified through the following three steps. The first step is to define a finite set of potential theater locations (hot spots) around the globe. A new theater is relevant for

[§]Data available online at http://www.fas.org/spp/military/program/imint/starlight.htm [cited 2001].

Table 2 Thin radar constellation: baseline assumptions

Parameter	Symbol	Nominal value	Source
Mission horizon	T_H	20 yr	Discoverer II
Required reaction time	R_{xn}	15 min	Discoverer II
Required availability	Av	90%	Discoverer II
Altitude	h_0	770 km	Discoverer II
Minimum grazing angle	$\varepsilon_{\min}$	6 deg (GMTI[a])	Discoverer II
Minimum nadir angle	$\eta_{\min}$	20°	Discoverer II
Minimum cone angle	$\beta_{\min}$	0 deg (GMTI)	Discoverer II
Theater frequency	ν	1 yr^{-1}	Adapted from Ref. 16
Mean time to refuel	μ_S	1 wk	Estimate from literature
Mean time to maneuver	T_M	[2 day; ∞]	Parameter
Satellite's specific impulse	I_{spC}	320 s	Chemical[14]
	$I_{\text{sp}E}$	299–3400 s	Electric[14]
Structure's mass factor	f_{st}	0.2	Robust design
Propulsion dry mass factor	f_p	0.15	Gamma Ray Observatory (GRO)[17]
Learning curve factor	B	0.926	95% slope
Hot spot latitudes	θ_n	48.51°, 45°, 42° 40.5°, 33.5°, 32° 31.9°, 30°, 13.8°, 0°	Assumed

[a]Ground moving target indicator.

the radar constellation only if it appears at a significantly different latitude. Thus, it is sufficient to define a finite number N_H of hot spots, each spot n representing a different region around the latitude θ_n and having the probability P_{Hn} to contain the most critical theater at any time. Numerical assumptions are summarized in Table 2 (where all spots are assumed equally probable). The second step consists of considering each possible number of satellites $\mathcal{T}$ and number of orbital planes $\mathcal{P}$ and, first, simulating the orbits to calculate availability and reaction time for each possible hot spot at each possible inclination i and phase number $\mathcal{F}$ and, then, deducing for each hot spot the set $\mathcal{I}(\theta_n) = [i_{\min}(\theta_n), i_{\max}(\theta_n)]$ of orbital inclinations at which there is a phase such that the constellation $\mathcal{T}/\mathcal{P}/\mathcal{F}$ meets the requirements (Av, Rxn). The required maneuverability for $\mathcal{T}/\mathcal{P}$ to be able to cover any hot spot is

$$\Delta i_{\text{req}}(\mathcal{T}, \mathcal{P}) = \max\left[0, \max_n(i_{\min}) - \min_n(i_{\max})\right] \tag{9}$$

The last step uses the principle that the number of satellites $\mathcal{T}$ is sufficient for a maneuverability $\Delta i_{\max}$ if there exists a number of planes $\mathcal{P}$ such that $\Delta i_{\text{req}}(\mathcal{T}, \mathcal{P}) \leq \Delta i_{\max}$. This relationship determines the minimum number of satellites as a function of maneuverability, $\mathcal{T}_{\min}(\Delta i_{\max})$.

This process quantifies the main advantage of maneuverability, which is to reduce the required number of satellites. Let us now consider the main drawback of maneuverability: the impact on satellite cost.

Maneuverable Satellite Propulsion System

The effect of maneuverability on the satellite cost is mainly dependent on the design of a propulsion system.

Chemical propulsion is well modeled as impulsive burns, so that the incremental velocity and the time required to perform an inclination change $\Delta i_{\max}$ are

$$\Delta V_{\max}^{\text{chem}} = 2V_0 \sin(\Delta i_{\max}/2) \tag{10}$$

$$\Delta T_{\max}^{\text{chem}} = 0 \tag{11}$$

Electric propulsion maneuvers on the other hand consist of low-thrust, continuous burns over long periods of time. Wertz and Larson[14] give the input power P_{in}, the thrust/power ratio T_P, the specific impulse I_{sp}, and the specific mass M_P for various existing electric propulsion systems (Ref. 14, Table 17-10, p. 703). The thrust available from N_T thrusters is $F = N_T T_P P_{\text{in}} = T_P P_{\text{input}}$. Because the maneuver is not instantaneous, the formula for inclination change $\delta V = 2V_0 \sin(\delta i/2)$ is valid for short timescales only. Making the approximation that the orbit remains circular at all points during the maneuver yields

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{1}{V_0}\frac{\mathrm{d}V}{\mathrm{d}t} \tag{12}$$

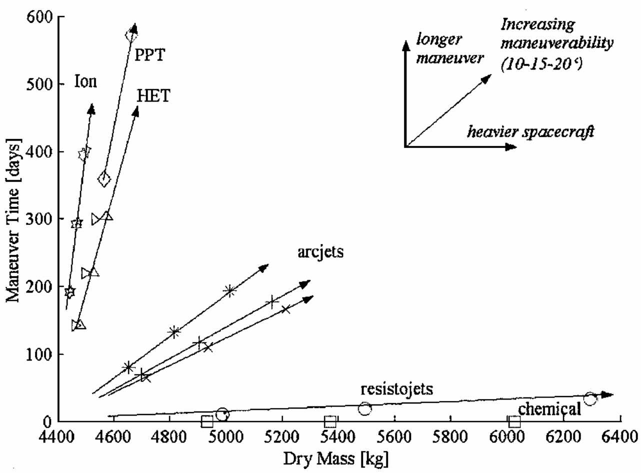

Fig. 8 Spacecraft mass vs time for inclination change for selected electric propulsion systems.

If the mass flow rate $\dot{M} = F/gI_{\text{sp}}$ is constant, then the total time for the maneuver can be estimated from the rocket equation, which finally yields

$$\Delta V_{\max}^{\text{elec}} = V_0|\Delta i_{\max}| \tag{13}$$

$$\Delta T_{\max}^{\text{elec}} = \frac{gI_{\text{sp}}}{T_P}\left[\exp\left(\frac{V_0|\Delta i_{\max}|}{gI_{\text{sp}}}\right) - 1\right]\frac{M_{\text{init}}}{P_{\text{input}}} \tag{14}$$

The spacecraft mass budget is then[15]

$$M_{\text{dry}}^{\text{tot}} = \frac{M_{\text{dry}}^{\text{base}}}{1 - (f_p + f_{\text{st}}f_p + \epsilon f_{\text{st}})[\exp(V_0|\Delta i_{\max}|/gI_{\text{sp}}) - 1]} \tag{15}$$

$$M_{\text{launch}} = M_{\text{dry}}^{\text{tot}}\{1 + \epsilon[\exp(V_0\,|\Delta i_{\max}|/gI_{\text{sp}}) - 1]\} \tag{16}$$

Figure 8 is a comparison of the mass increase and the time for a given inclination change, for a spacecraft with $M_{\text{dry}}^{\text{base}} = 4400$ kg and $P_{\text{input}} = 10$ kW. It shows that without any increase in available power, the mass savings allowed by electric propulsion come at the expense of very long maneuver times.

Calculating Value

The basic elements of the flexibility valuation take a special form here due to the on-demand character of servicing and the peculiar military decision process.

Decision Process

The uncertain parameter is the latitude $X = \theta$ of the current critical theater of action. The historical occurrence of world contingencies

Table 3 Summary of thinned constellation valuation process

Equation	Description
$V = \dfrac{E\{U\}}{E\{C\}}$	Mission value
$E\{U\} = \overline{T_o}\,\overline{u_o} + \overline{T_{no}}\,\overline{u_{no}}$	Expected utility
$E\{C\} = C_{\mathrm{IOC}}(N_{\mathrm{sat}} + N_R,\, \Delta i_{\max}) + N_S \bar{C}$	Expected cost, where
$\overline{T_o} = \int_0^{T_H} [P_1(t) + P_2(t)]\, dt$	Time spent with optimized configuration
$\overline{u_o} = \sum_{n=1}^{N_H} \hat{\eta}(\theta_n)$	Average utility rate if optimized configuration
$\overline{T_{no}} = \int_0^{T_H} [P_3(t) + P_4(t)]\, dt$	Time spent with nonoptimized configuration
$\overline{u_{no}} = \sum_{n=1}^{N_H} \sum_{m \neq n} \eta(\theta_n, \widehat{\mathcal{C}_m})$	Average utility rate if nonoptimized configuration
$N_R = \int_0^{T_H} \mu_R e^{-rt} P_5(t)\, dt$	Discounted number of replacements
$N_S = \int_0^{T_H} \mu_S e^{-rt} [P_2(t) + P_4(t)]\, dt$	Discounted number of servicings
$\bar{C} = \sum_{n=1}^{N_H} \sum_{n \neq m} \dfrac{P_{Hn} P_{Hm}}{1 - P_{Hn}} C^{(n \leftrightarrow m)}$	Average cost to change configuration

has been similar to a Poisson process (see Ref. 16), so that the probability that the theater changes between t and $t + dt$ is of the form νdt where ν is the theater frequency.

The utility rate is the ratio of time in view ζ of the current constellation configuration n over the current theater latitude X: $u^{(n)}(X) = \zeta(X, \mathcal{C}_n)$. At each decision point, the chosen mode of operation must be the configuration $\widehat{\mathcal{C}_n} = (\widehat{\iota_n}, \widehat{F_n})$ that optimizes the performance over the current hot spot n, that is, that gives the highest ratio of time in view $\widehat{\zeta}$ over the target. Because the theater can move at any time, decision points must be continuous. The system can be kept independent of history by defining a maneuver rate $\mu_M = 1/T_M$, so that the probability to have finished the maneuver verifies $dP = \mu_M(1 - P)\, dt$.

Costs

The main impact of maneuverability is mass. Because the added mass is primarily made up of fuel and structures to support it, it is reasonable to assume that the development and production costs do not depend on maneuverability. The cost to IOC is then a function of the number of satellites in the constellation and their maneuverability, as follows:

$$C_{\mathrm{IOC}} = C_D + N_{\mathrm{sat}}^B C_P + \frac{1 + \epsilon[\exp(V_0|\Delta i_{\max}|/g I_{\mathrm{sp}}) - 1]}{1 - (\epsilon f_{\mathrm{st}} + f_p + f_p f_{\mathrm{st}})[\exp(V_0|\Delta i_{\max}|/g I_{\mathrm{sp}}) - 1]} \times N_{\mathrm{sat}} M_{\mathrm{dry}}^{\mathrm{base}} C_L \tag{17}$$

Switching modes of operation requires refueling. The incremental velocity to maneuver between configurations m and n is a function of their difference in inclination $|\widehat{\iota_m} - \widehat{\iota_n}|$, as given by Eqs. (13) or (15). The mass of fuel to be delivered is then $M_{\mathrm{fuel}}^{(m \to n)} = M_{\mathrm{dry}}[\exp(\Delta V / I_{\mathrm{sp}} g) - 1]$, so that, if there is a constant servicing price C_{Sm} per unit mass delivered, the cost to switch modes is of the form

$$C^{(m \leftrightarrow n)} = \frac{\exp\left(\Delta V^{(m \leftrightarrow n)} / I_{\mathrm{sp}} g\right) - 1}{1 - (\epsilon f_{\mathrm{st}} + f_p + f_p f_{\mathrm{st}})[\exp(V_0|\Delta i_{\max}|/g I_{\mathrm{sp}}) - 1]} \times M_{\mathrm{dry}}^{\mathrm{base}} C_{Sm} \tag{18}$$

Value Model

In this study, the decision model is to optimize performance continuously instead of maximizing future value. The best method to estimate value in this case is a Markov model. This model has the further advantage of facilitating the introduction of a servicing rate μ_S and a probability of a crash P_C. At least five states are necessary to describe the constellation behavior, as shown by Fig. 9. The final calculation of the mission value is summarized in Table 3.

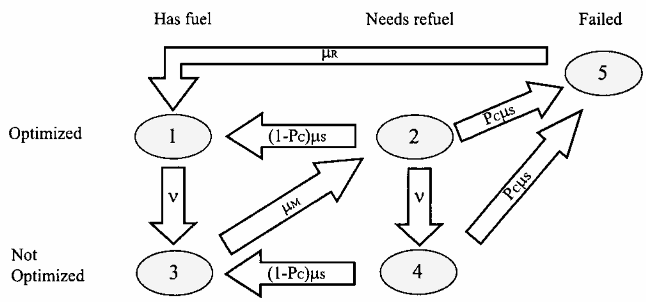

Fig. 9 Markov model for a maneuverable radar constellation.

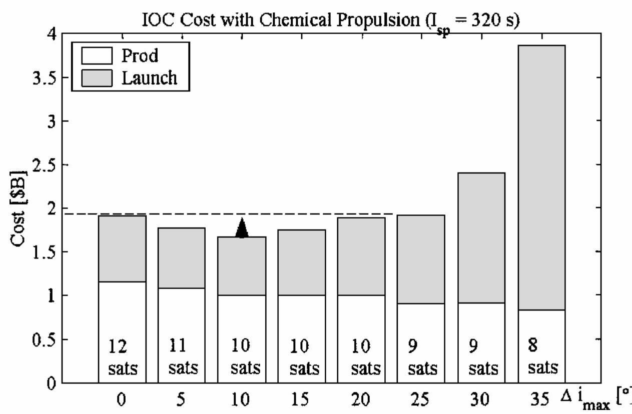

Fig. 10 Chemical propulsion: IOC cost as function of maneuverability.

Results for Baseline Case

The stage is now ready to consider the numerical results for the baseline assumptions summarized in Table 2 (see Refs. 14, 16, and 17).

Chemical Propulsion

Chemical propulsion offers the great advantage of minimizing the time for an inclination change, but this comes at the expense of an exponential mass increase. Figure 10 shows the minimum cost

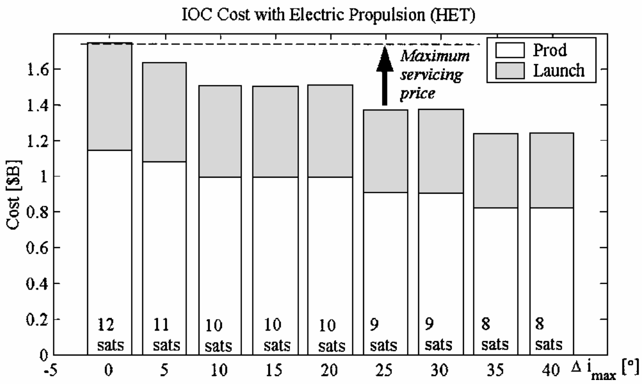

Fig. 11 Electric propulsion: IOC cost for null servicing price.

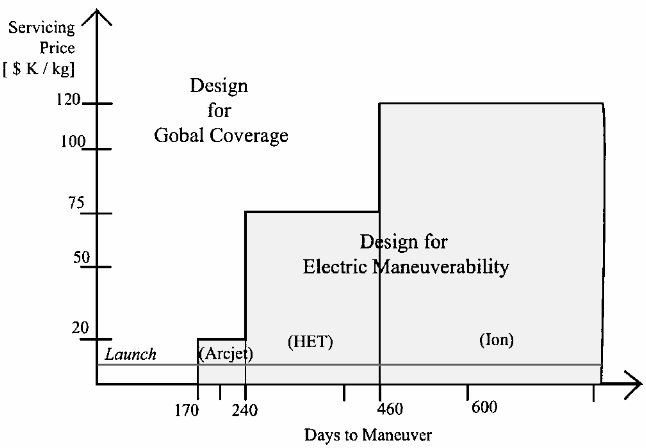

Fig. 12 Electric propulsion: maximum servicing price per unit mass vs time to allowed to maneuver.

of a constellation to IOC as a function of its maneuverability. As the required number of satellites decreases, production costs decrease linearly, while launch costs increase exponentially as a result of the exponential mass increase. A very slight minimum of cost and maximum of utility per cost is observed for a maneuverability $\widehat{\Delta i}_{\max} = 10$ deg. However, the difference with zero maneuverability is so slight that it allows no room for servicing price: Whatever the price of servicing, chemical maneuverability cannot be interesting for this radar constellation. Note that this is true whatever the design of a servicing infrastructure, which shows the advantage of studying the value of servicing before attempting to model its cost.

Electric Propulsion

An upper bound on the value of servicing can be found by assuming that there is no limit to the allowed time to maneuver and considering electric propulsion. For a sufficiently high specific impulse, the impact of maneuverability on spacecraft mass becomes negligible, so that the total cost to IOC decreases with increasing maneuverability as seen in Fig. 11. However, the higher the maneuverability, the higher the total mass is that must be delivered to the constellation over the lifetime of the mission. Considering the difference in utility per cost between the maneuverable and nonmaneuverable cases, one can determine the maximum servicing price per unit mass under which the optimal design is maneuverable.

The results are summarized in Fig. 12. The maximum servicing price is found to be greater than four times the cost to launch to LEO for any electric propulsion system but arcjets and resistojets. Thus, if the price of servicing is kept close to the marginal servicing cost, an electric thinned constellation is more cost effective than a global coverage, nonmaneuverable constellation. However, this must be traded against maneuver time. The maneuver time that makes electric propulsion optimal is of the order of a year for the baseline satellite mass and power. Given that no power is available for the payload during a maneuver, such a long time is unacceptable in the critical context of radar coverage of a military theater of action.

Conclusion

These results suggest that refueling would have no value for a LEO radar constellation unless revolutionary propulsion technologies, offering high thrust and high specific impulse, were developed. Inclination change is obviously not the optimal way to improve coverage, and other options should of course be explored, such as other forms of maneuverability, or chemical propulsion with stepwise inclination change (refueling after each step). However, such studies are outside the bounds of this research effort. Instead, we will use this generalization of the framework to study another military case, for which the incremental velocity for maneuvering is less problematic.

Military Communications Under Uncertain Contingency Locations

The uncertainty in the occurrence and location of contingencies does not affect only radar satellites. There is also a need for flexibility in the distribution of the military communication satellites capacity. This flexibility could be achieved by making the satellites maneuverable, so that they can optimize their longitudes as a function of the distribution of contingencies. Changes in longitude require only small incremental velocities even for a short allowed maneuvering time, thus solving the problem faced in the preceding section. Is this enough to make refueling of significant value? Let us make simple assumptions to get a first-order answer to this question.

Modeling Value

A simple model of the situation can be developed in a similar fashion as for the thinned constellation case.

Decision Model

Assume that the total number of contingencies to be covered around the world is a constant N_C. The uncertainty lies in the distribution of these contingencies as a function of longitude. It is practical to divide the globe in N_R regions and define the uncertain parameter as the vector $\boldsymbol{X} = (\boldsymbol{X}_1, \ldots, \boldsymbol{X}_{N_R})$ describing the number of contingencies that lie in each region. If at any time all contingencies have the same probability $p = 1/N_R$ to occur in each region, the probability that the distribution of contingencies be $\mathcal{C} = (\boldsymbol{X}_1, \boldsymbol{X}_2, \ldots, \boldsymbol{X}_{N_R})$ is

$$P\{(X_1, X_2, \ldots, X_{N_R})\} = p^a (1-p)^b \left(N_C! \middle/ \prod_{i=1}^{N_R} X_i! \right) \tag{19}$$

with

$$a = \sum_{k=1}^{N_R - 1} X_i, \qquad b = (N_R - 1)N_C - \sum_{k=1}^{N_R - 1} k X_{N_R - k} \tag{20}$$

The fleet is made up of N_{sat} military GEO satellites whose only degree of freedom is their longitude. The possible modes of operation are the distributions of the fleet over the N_R regions $\mathcal{C} = (n_1, n_2, \ldots, n_{N_R})$, where n_k is the number of satellites attributed to region k.

The decision model is independent of time: It says to maximize the performance of the current system. Maximum performance is achieved by maneuvering into the optimal distribution of satellites $n_k = I(X_k N_{\text{sat}}/N_C)$ as soon as demand is redistributed. The decision process is made continuous by introducing a maneuver rate $\mu_M = 1/\Delta T_{\max}$ and a contingency frequency ν_c, defined as the rate at which contingencies appear.

The demand is expressed in terms of total capacity required over the world. The utility of the system can be defined as the percentage of data transfer required that has been provided over the lifetime of the mission. The utility rate at t is then the percentage of the capacity required, $\mathcal{R}(t)$, that is provided at t. If several satellites above the same region can be used at their full capacity R, then this is

$$u(X, t) = \frac{1}{\mathcal{R}(t)} \sum_{k=1}^{N_R} \min\left(n_k R, \frac{\mathcal{R}(t) X_k}{N_C} \right) \tag{21}$$

The expected utility rate can be computed using Eqs. (19) and (21) for optimized $\overline{u_o}$ and nonoptimized $\overline{u_{no}}$ configurations.

Costs

Changing longitude corresponds to a phasing maneuver, which can be accomplished by altering the apogee of the orbit so that the slightly different period cancels out the difference in phase. The required incremental velocity depends on the time $\Delta T_{\max}$ allowed to perform the maneuver[15]:

$$\Delta V(\Delta\Phi, \Delta T_{\max}) = 2V_0\left|-1+\sqrt{2-\left[\frac{I(\Delta T_{\max}/T_0+\Delta\Phi/2\pi)}{I(\Delta T_{\max}/T_0+\Delta\Phi/2\pi)-\Delta\Phi/2\pi}\right]^{\frac{2}{3}}}\right| \quad (22)$$

To optimize communications availability, a satellite will maneuver by $n\Delta\Phi$ whenever capacity must be moved between two regions separated in longitude by an angle $n\Delta\Phi$. The satellites can be assumed to be refueled after each maneuver, as well as every time they have performed $\Delta V_{\max}$ for station keeping. Their design ΔV is, therefore,

$$\Delta V_d = \max\{\Delta V_{\text{ins}}, \Delta V(\pi, \Delta T_{\max})\} \quad (23)$$

The mass budget is then the same as for the chemical radar constellation considered in the preceding section. If the price to service per unit of delivered mass is C_{Sm}, then the price to refuel after a change of longitude $\Delta\Phi$ is

$$C(\Delta\Phi) = \frac{\exp\{[\Delta V(\Delta\Phi, \Delta T_{\max})]/I_{\text{sp}}g\}-1}{1-(\epsilon f_{\text{st}}+f_p+f_p f_{\text{st}})[\exp(\Delta V_d/gI_{\text{sp}})-1]} \times M_{\text{dry}}^{\text{base}}C_S = x(\Delta\Phi)M_{\text{dry}}^{\text{base}}C_{Sm} \quad (24)$$

The average fuel cost for a maneuver is, therefore,

$$\overline{C_S} = \overline{x_S}M_{\text{dry}}^{\text{base}}C_{Sm}$$

where

$$\overline{x_S} = \begin{cases} \dfrac{1}{l}\displaystyle\sum_{k=1}^{l} x(k\Delta\Phi) & \text{if} \quad N_R = 2l+1 \\ \dfrac{1}{2l-1}x(l\Delta\Phi) + \dfrac{2}{2l-1}\displaystyle\sum_{k=1}^{l} x(k\Delta\Phi) & \text{if} \quad N_R = 2l \end{cases}$$

Markov Model

On-demand maneuvering can be modeled as a Markov process. The performance of the fleet can be described by two states: optimized configuration o and nonoptimized configuration no. Transitions from o to no occur with rate $\nu = N_{\text{sat}}\nu_c/N_C$, whereas satellites maneuver with rate μ_M from state no to state o. To take into account the effect of the servicing rate μ_S, each state must be divided into $(N_{\text{sat}}+1)$ substates, where substates k mean k satellites need to be refueled. Finally, to account for a nonzero probability of catastrophic event P_C, we must consider the failed state f and the replacement rate μ_R. The resulting state transitions are summarized in Fig. 13 (where $N_{\text{sat}} = 2$ for clarity).

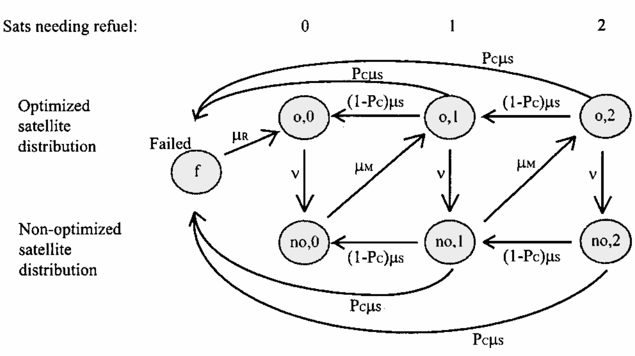

Fig. 13 Markov model for maneuverable milcomm. GEO fleet.

The discounted number of attempted servicing events is then

$$N_{\text{serv}} = \mu_S\int_0^{T_H} e^{-rt}\,\mathrm{d}t\sum_{k=1}^{N_{\text{sat}}}[P_{o,k}(t)+P_{no,k}(t)] \quad (25)$$

The discounted number of satellite replacements due to servicing catastrophic events is

$$N_{\text{rep}} = \mu_R\int_0^{T_H} e^{-rt}P_f(t)\,\mathrm{d}t \quad (26)$$

The final value is given by $V = E\{U\}/E\{C\}$ with

$$E\{U\} = \int_0^{T_H} P_o(t)\overline{u_o}(t)\,\mathrm{d}t + \int_0^{T_H} P_{no}(t)\overline{u_{no}}(t)\,\mathrm{d}t \quad (27)$$

$$E\{C\} = C_{\text{IOC}}(N_{\text{sat}}+N_{\text{rep}}, \Delta V_d) + N_{\text{serv}}\overline{C_S} \quad (28)$$

Threshold Servicing Price

The maximum servicing price per unit mass Υ is the servicing price under which the value of the maneuverable fleet is greater than the value of the baseline fleet $V_b = E\{U_b\}/E\{C_b\}$:

$$\Upsilon = \frac{E\{C_b\}E\{U\}/E\{U_b\}-(N_{\text{sat}}+N_{\text{rep}}\Delta V_d)C_{\text{IOC}}}{N_{\text{serv}}\overline{x_S}M_{\text{dry}}^{\text{base}}} \quad (29)$$

Results

Let us consider as our baseline satellite fleet the DSCS satellites. The corresponding numerical assumptions can be found in Table 4. The overall demand is expected to increase with time at an approximate rate 1 Gbps/year starting from a current value of 3 Gbps (Ref. 16). For our purposes it is sufficient to define the demand in terms of a percentage compared to its present value, so that $\mathcal{R}(t) = 1 + a_{\mathcal{R}}t$ with $a_{\mathcal{R}} = \frac{1}{3}$ year^{-1}. Let us further assume that the demand is exactly met by the current satellite fleet, so that $N_{\text{sat}}R = 1$.

Improvement in Utility

With a maneuverable constellation, the capacity of the fleet is almost fully exploited at any time. With a baseline fleet on the other hand, some satellites are wasted over areas with small number of contingencies, whereas others would be needed where contingencies concentrate. Therefore, the utility of the baseline fleet is smaller than the utility of the maneuverable fleet. For the baseline case, maneuverability enables a 20% improvement in utility. This result is slightly sensitive to the number of contingencies: the more numerous the contingencies requiring the same overall capacity, the smaller

Table 4 Maneuverable fleet of GEO military communication satellites: numerical assumptions

Parameter	Name	Value	Source
Number of conflicts	N_C	10	Adapted from Ref. 16
Number of regions	N_R	5	DSCS satellites coverage
Number of satellites	N_{sat}	9	DSCS satellites
Contingency frequency	ν_c	3/yr	Adapted from Ref. 16
Maximum time to maneuver	$\Delta T_{\max}$	2 day	Priority estimate
Mission horizon	T_H	10 yr	DSCS design lifetime
Orbit insertion ΔV	ΔV_{ins}	0 m/s	Use upper stage
Specific impulse	I_{sp}	320 s	Chemical propulsion
Fuel fraction at launch	ε	1	Not too heavy
Structures mass factor	f_{st}	0.2	Robust design
Propulsion dry mass factor	f_p	0.15	GRO[17]
Baseline unit cost	C_u	$200 million	DSCS (web)
Cost of launch	C_L	$30,000/kg	DSCS launchers
Risk-free interest rate	r	7%	Typical
Baseline satellite mass	M_{base}	1,170 kg	DSCS
Servicing rate	μ_S	1/(7 day)	Estimate
Probability of crash	P_C	0.001	Assumption
Replacement rate	μ_M	3/yr	Estimate

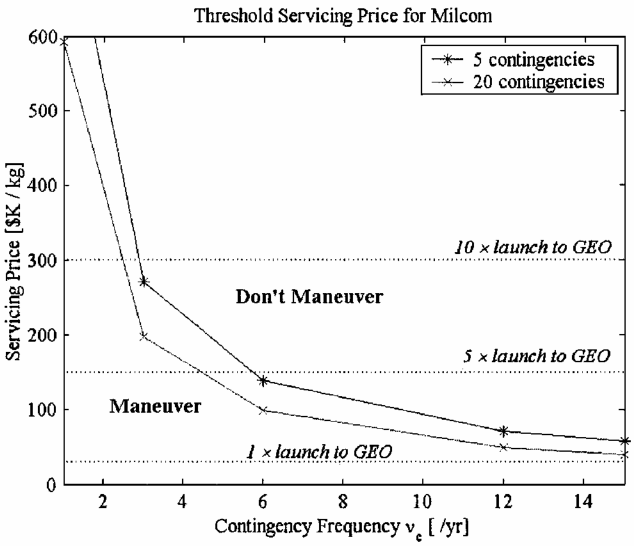

Fig. 14 Threshold servicing price as a function of contingency frequency.

the relative deviations from a uniform distribution of contingencies over longitude, and, therefore, the smaller the capacity wasted by the baseline fleet. This does not account for the real world fact that the number of GEO orbital slots is constrained. The point is to see if there are any cases in which on-orbit servicing begins to be interesting.

Maximum Servicing Price

Figure 14 plots the maximum servicing price Υ as a function of the number of simultaneous contingencies and the contingency frequency. For the baseline values, the maximum servicing price is $220,000/kg, which is more than seven times the cost to launch to GEO. Thus, servicing would be significantly interesting for this case as soon as the fleet of satellites pay only the marginal cost of servicing, that is, the cost to produce and launch the fuel to deliver plus the corresponding servicer vehicles.

The maximum servicing price decreases at higher contingency frequencies because of the increasing number of maneuvers necessary per year. For $\nu_c = 12$/year, the maximum servicing price is of the order of the cost to launch to GEO: Following the contingencies becomes too expensive compared to the increase in utility. Υ also decreases with increasing number of contingencies, as a result of the increasing utility of the baseline constellation. For the baseline $\nu_c = 3$/year, the maximum servicing price, however, always remains an order of magnitude higher than the launch cost.

Sensitivity studies all indicate that the same conclusions hold for any realistic value of the other assumed parameters. Thus, the maneuverability concept is promising for a fleet of GEO satellites. The maximum servicing price is an order of magnitude greater than the cost to launch mass into geostationary orbit, which guarantees that servicing may be interesting for realistic marginal infrastructure costs and serviceability development costs.

Conclusions

There is value in the options that on-orbit servicing would provide to space systems. Because this flexibility has not been accounted for, traditional valuation methods have been underestimating the value of servicing.

The companion paper proposed a general framework to take into account the value of the flexibility to react to any source of uncertainty that can be modeled as external. This paper demonstrated how this framework can be successfully applied to develop models for the value of servicing in the presence of uncertainty for a variety of situations. It showed that options can make up a significant fraction of total space mission value as soon as the uncertainty is significant. Because they do not require to estimate the cost of any on-orbit servicing infrastructure, these results are not plagued by the high servicing cost uncertainty.

The systematic application of this framework should prove very useful in identifying the space missions for which on-orbit servicing would offer the most potentials. It should serve as a guide for future on-orbit servicing technology development as to what maximum price can be charged to various types of space missions. More generally, it can be used by space missions as a new tool for decision making, with which the value of flexibility, seen as a means to actively manage external sources of uncertainty, can be quantified.

Acknowledgments

This research was supported by the Defense Advanced Research Project Agency (DARPA) Grand Challenges in Space ASTRO/Orbital Contract F29601-97-K-0010. Daniel E. Hastings would like to acknowledge useful discussions with David Whelan (currently at The Boeing Company), James Shoemaker at DARPA, and Roger DeKok at the U.S. Air Force Space Command.

References

[1]Waltz, D. M., *On-Orbit Servicing of Space Systems*, Krieger, Malabar, FL, 1993.

[2]Davinic, N. D., Chappie, S., Arkus, A., and Greenberg, J., "Spacecraft Modular Architecture Design Study: Cost Benefit Analysis of On-Orbit Satellite Servicing," International Academy of Astronautics, IAA Paper 97-1.4.07, Oct. 1997.

[3]Leisman, G., Wallen, A., Kramer, S., and Murdock, W., "Analysis and Preliminary Design of On-Orbit Servicing Architectures for the GPS Constellation," AIAA Paper 99-4425, Sept. 1999.

[4]Leisman, G., "Analysis of On-Orbit Servicing Architectures Using Microsatellites, Advanced Propulsion, Secondary Payload Opportunities and the Military Spaceplane Concept," AIAA Paper 2000-5288, Sept. 2000.

[5]Cuplin, L., and Chun, W. H., "Satellite Servicing and Space Logistics," AIAA Paper 2000-5289, Sept. 2000.

[6]Saleh, J. H., Lamassoure, E., and Hastings, D. E., "Space Systems Flexibility Provided by On-Orbit Servicing: Part 1," *Journal of Spacecraft and Rockets*, Vol. 39, No. 4, 2002, pp. 551–560.

[7]Saleh, J. H., Hastings, D. E., and Newman, D. J., "Spacecraft Design Lifetime," *Journal Spacecraft and Rockets*, Vol. 39, No. 2, 2002, pp. 244–257.

[8]Trigeorgis, L., *Real Options; Managerial Flexibility and Strategy in Resource Allocation*, MIT Press, Cambridge, MA, 1996.

[9]Leisman, G. A., and Wallen, A. D., "Design and Analysis of On-Orbit Servicing Architectures for the Global Positioning System Constellation," M.S. Thesis, U.S. Air Force Inst. of Technology, Wright–Patterson AFB, OH, March 1999.

[10]Harbison, J. R., Moorman, T. S., Jr., Jonesa, M. W., and Kim, J., *Viewpoint: U.S. Defense Industry Under Siege—An Agenda for Change*, Booz Allen and Hamilton, New York, 2000.

[11]Merton, R. C., "An Intertemporal Capital Asset Pricing Model," *Econometrica*, No. 41, Sept. 1973, pp. 867–887.

[12]Gumbert, C. C., Violet, M. D., Hastings, D. E., Hollister, W. M., and Lovell, R. R., "Cost per Billable Minute Metric for Comparing Satellite Systems," *Journal of Spacecraft and Rockets*, Vol. 34, No. 6, 1997, pp. 837–346.

[13]Walker, J. G., "Some Circular Orbit Patterns Providing Continuous Whole Earth Coverage," *Journal of the British Interplanetary Society*, Vol. 24, 1971, pp. 369–384.

[14]Wertz, J. R., and Larson, W. J., *Space Mission Analysis and Design*, 3rd ed., Space Technology Series, Microcosm and Kluwer Academic, Noewell, MA, 1999, p. 703.

[15]Lamassoure, E., "A Framework to Account for Flexibility in Modeling the Value of On-Orbit Servicing for Space Systems," M.S. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, June 2001.

[16]Bonds, T., Mattock, M. G., Hamilton, T., Rhodes, C., Scheiern, M., Feldman, P. M., Frelinger, D. R., and Uly, R., *Employing Commercial Satellite Communications; Wideband Investment Options for the Department of Defense*, Project Air Force RAND, Santa Monica, CA, 2000.

[17]Weatherly, J. A., Carlson, R. A., and Hevert, S. C., "The Gamma Ray Observatory (GRO) Propulsion Systems," AIAA Paper 88-3051, July 1988.

A. C. Tribble
Associate Editor